

## Solar Electric Propulsion

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The Solar Electric Propulsion (SEP) technology area is tasked to develop near and mid-term SEP technology to improve or enable science mission capture while minimizing risk and cost to the end user.

The solar electric propulsion investments are primarily driven by SMD cost-capped mission needs. The technology needs are determined partially through systems analysis tasks including the recent “Re-focus Studies” and “Standard Architecture Study.” These systems analysis tasks transitioned the technology development to address the near term propulsion needs suitable for cost-capped open solicited missions such as Discovery and New Frontiers Class missions.

Major SEP activities include NASA’s Evolutionary Xenon Thruster (NEXT), implementing a Standard Architecture for NSTAR and NEXT EP systems, and developing a long life High Voltage Hall Accelerator (HiVHAC). Lower level investments include advanced feed system development and xenon recovery testing.

Future plans include completion of ongoing ISP development activities and evaluating potential use of commercial electric propulsion systems for SMD applications. Examples of enhanced mission capability and technology readiness dates shall be discussed.



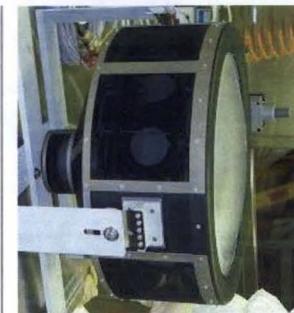


# Solar Electric Propulsion

SEP Technology Area Mgr: Michael LaPointe, NASA Marshall Space Flight Center

## Objective

- Overall: Develop SEP technology that will enable missions to new science destinations and increase the science return over existing capabilities by reducing mission cost, risk, and trip times.
- NEXT: Advance gridded-ion propulsion technology for higher performance and higher power capability.
- HiVHAC: Advance the performance and life of Hall thruster technology to significantly reduce the cost of electric propulsion applicable for Discovery class missions.
- VACCO: Advance xenon feed system technology that can be used with either gridded-ion or Hall thruster systems to increase reliability while decreasing mass and volume.



SEP Products

## Approach

- Evaluate mission needs and requirements for potential science mission applications.
- Develop new technologies that address the needs of SMD.
- Leverage commercial electric propulsion systems that have potential to provide production unit products applicable to science missions.

## PIs:

NEXT: Michael Patterson, GRC

HiVHAC: David Manzella, GRC

VACCO: Joseph Cardin, VACCO

Participating Team Members: JPL, GRC, Aerojet, L3-Comm  
ETI, Swales, U. of Michigan, APL-JHU, and CSU

## Key Milestones

- NEXT: PM1 performance test 3/06  
PM1 thruster environmental test 6/06  
EM PPU delivery to GRC 8/06  
Gimbal/thruster vibration test 6/06  
8,000 hrs of wear test complete 10/06
- HiVHAC: NASA-94M (SOA) performance test 7/06  
NASA-94M(ASOA) performance test 8/06  
NASA-94M(ASOA) wear test 10/06
- VACCO: Flow control module test 7/06  
Pressure control module delivery 2/07



# Solar Electric Propulsion

*In Space Propulsion Technology Project  
NASA Marshall Space Flight Center*

*Dr. Michael LaPointe*

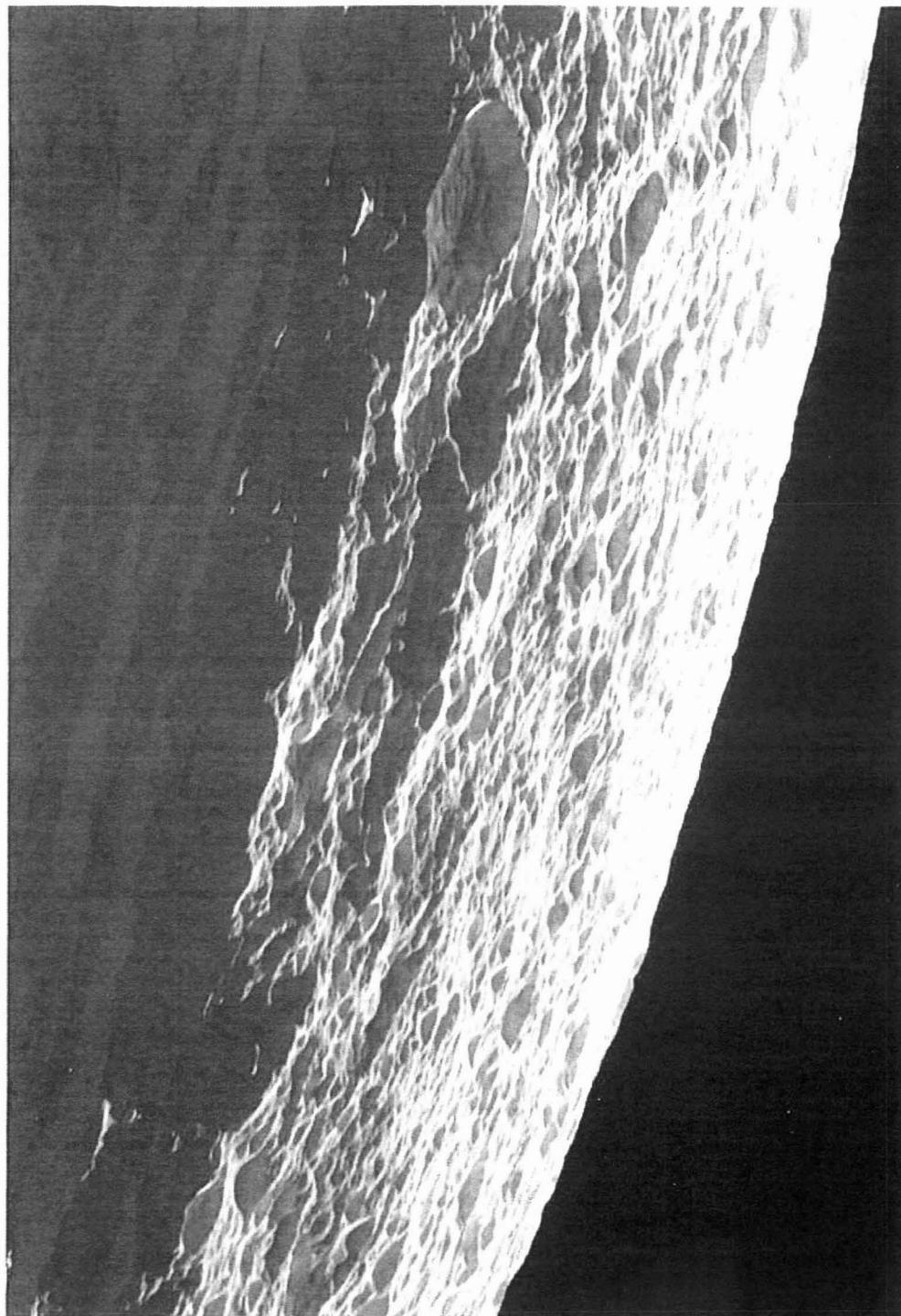
*Earth Science Technology Conference 2006*

*June 27-29, 2006*



## Outline

- **Background: Why the Interest in Solar Electric Propulsion?**
- **Types of Electric Thrusters: a Quick Review**
- **Primary In-Space Propulsion Program SEP Task Areas**
- **Future Directions**



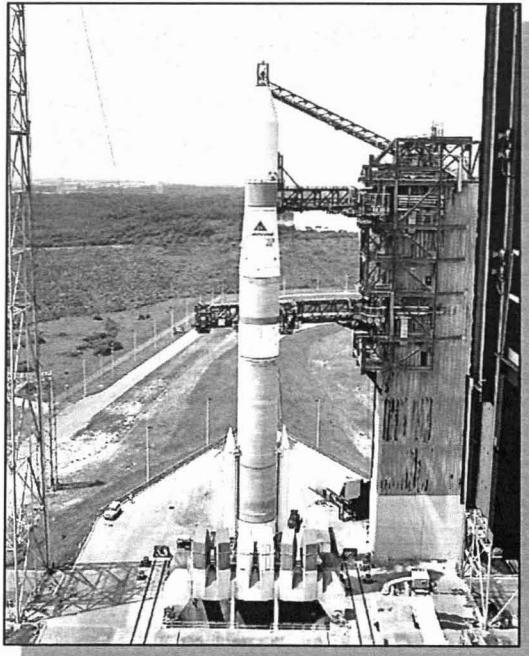


## Background

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**Chemical propulsion** converts the energy stored in the molecular bonds of a propellant into kinetic energy

- Typically high thrust to weight (required for launch)
- But the exhaust velocity is limited by the chemical energy available
- Why is this important?



$$\frac{M_f}{M_0} = \exp\left[-\frac{\Delta V}{V_e}\right]$$

- For a given change in velocity ( $\Delta V$ ), the delivered mass ( $M_f$ ) depends on the propellant exhaust velocity ( $v_e$ )
- More propellant is required to provide a given impulse at lower exhaust velocities



**Electric propulsion** (EP) uses electrical power to provide kinetic energy to a gas propellant

- Decouples kinetic energy from limitations of chemical energy
- Provides higher exhaust velocities than chemical engines
  - Reduces propellant mass needed to provide a given impulse
  - Allows reduction in launch mass or increase in payload; can provide substantial benefits in mission cost
- Electric propulsion primarily benefits large total impulse missions
  - Orbit raising, repositioning, long-term station keeping
  - Robotic planetary and deep space science missions
  - Precise impulse bits for formation flying (pulsed EP systems)
- Electric propulsion employed on over 180 spacecraft, including EO-1 (earth observation), SMART-1 (lunar mission), and DS-1 (comet fly-by), with DAWN (asteroid mission) to launch in 2007

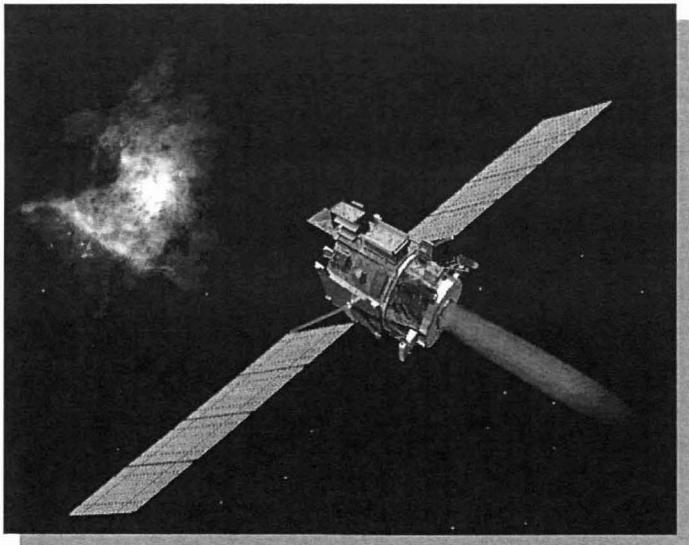


## Background

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### Additional considerations...

- Lower thrust to weight than chemical engines
  - Small but steady acceleration, vs. short-burn chemical engines
  - EP engines must be designed for long life (thousands of hours)



- Increased dry mass due to:
  - Solar arrays
  - Power processing unit
  - Other EP specific hardware
- Spacecraft integration considerations:
  - Electric power requirements
  - Plasma plume and potential EMI
- Propulsion system trades performed to evaluate whether a given mission will benefit from the use of electric propulsion



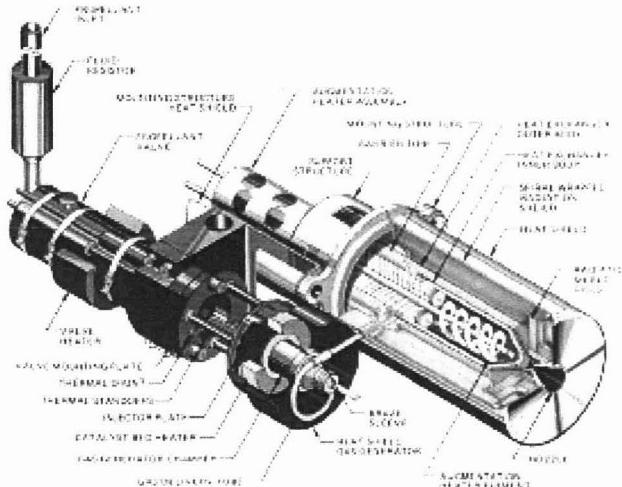
**Electric thrusters are generally categorized by their primary acceleration mechanism:**

- Electrothermal
  - Resistojet (commercial flight units available)
  - Arcjet (commercial flight units available)
- Electrostatic
  - Hall effect thrusters (commercial flight units + development)
  - Gridded ion thrusters (commercial flight units + development)
- Electromagnetic
  - Pulsed plasma thruster (commercial flight units available)
  - Magnetoplasmadynamic thruster (laboratory models only)
  - Pulsed inductive thruster (laboratory models only)

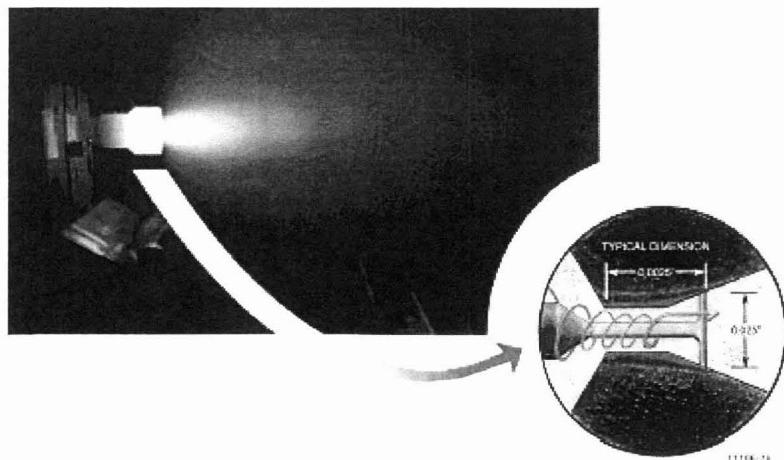
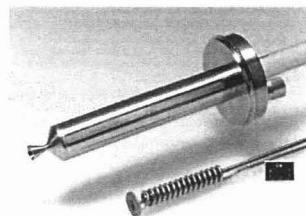
## ***Electrothermal Thrusters***



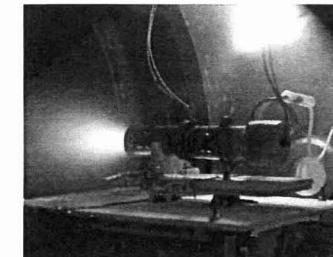
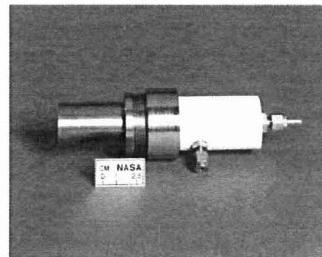
- heat gas and expand through a nozzle



**Resistojet** thrusters use resistive heating elements to increase the thermal energy of a gas propellant

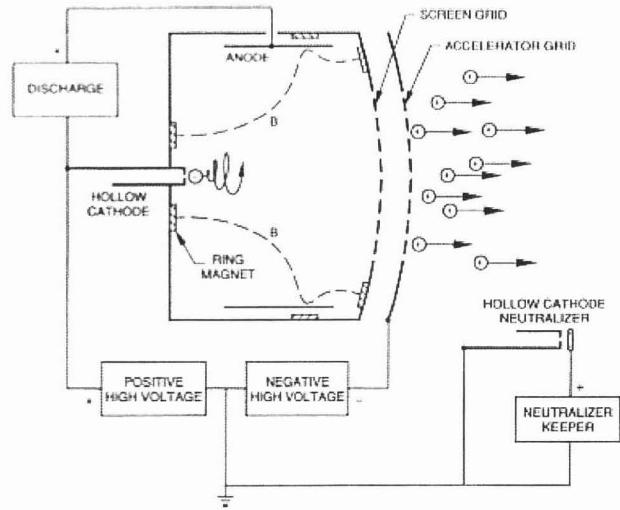


**Arcjet** thrusters use an electric arc to increase the thermal energy of a gas propellant

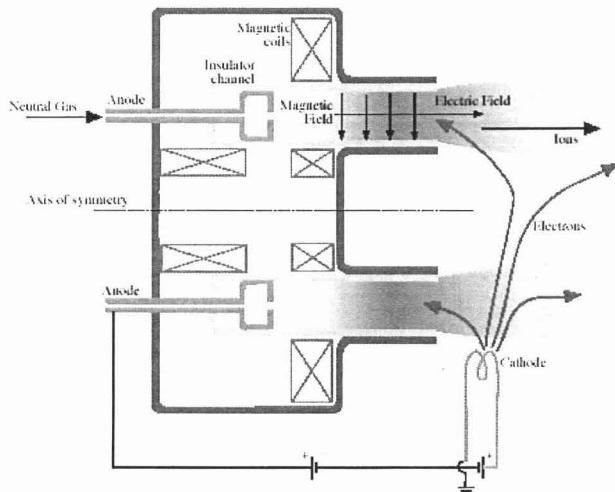
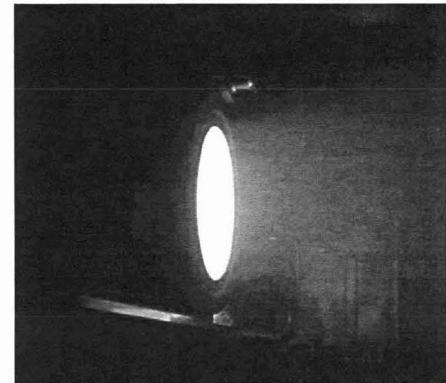


# Electrostatic Thrusters

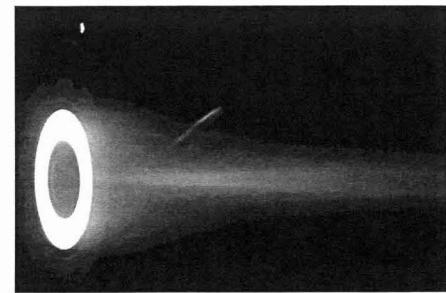
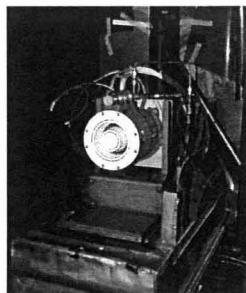
- generate high voltages for ion (plasma) acceleration



Ion thrusters use closely spaced high voltage grids to create an electrostatic field



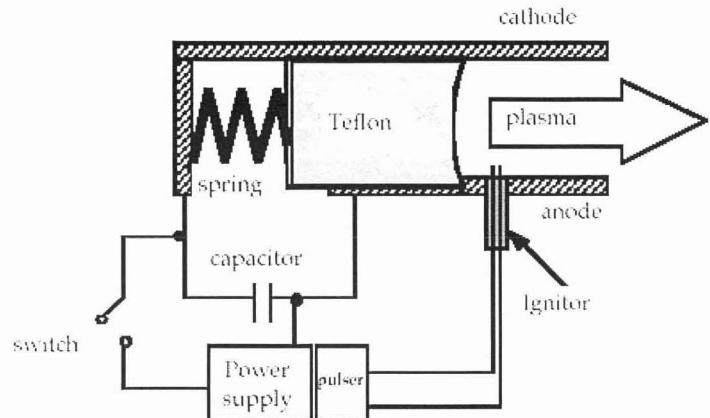
Hall thrusters use magnetically trapped electrons to create an electrostatic field



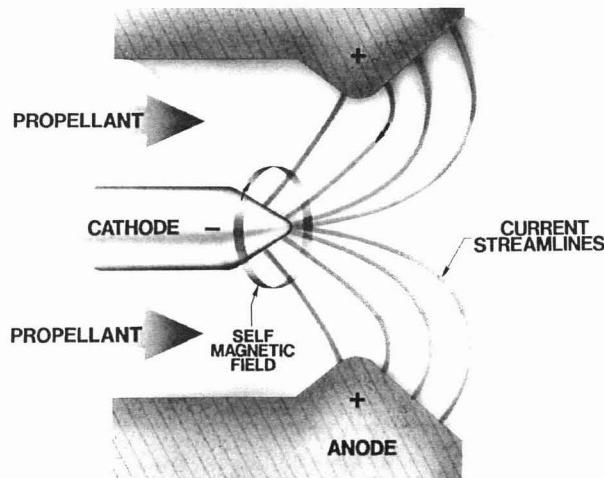
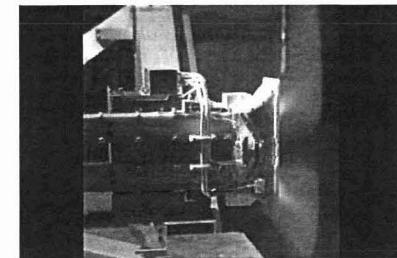
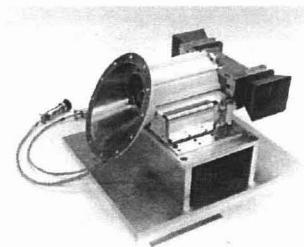
# Electromagnetic Thrusters



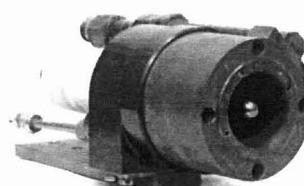
- apply a Lorentz ( $J \times B$ ) force for plasma acceleration



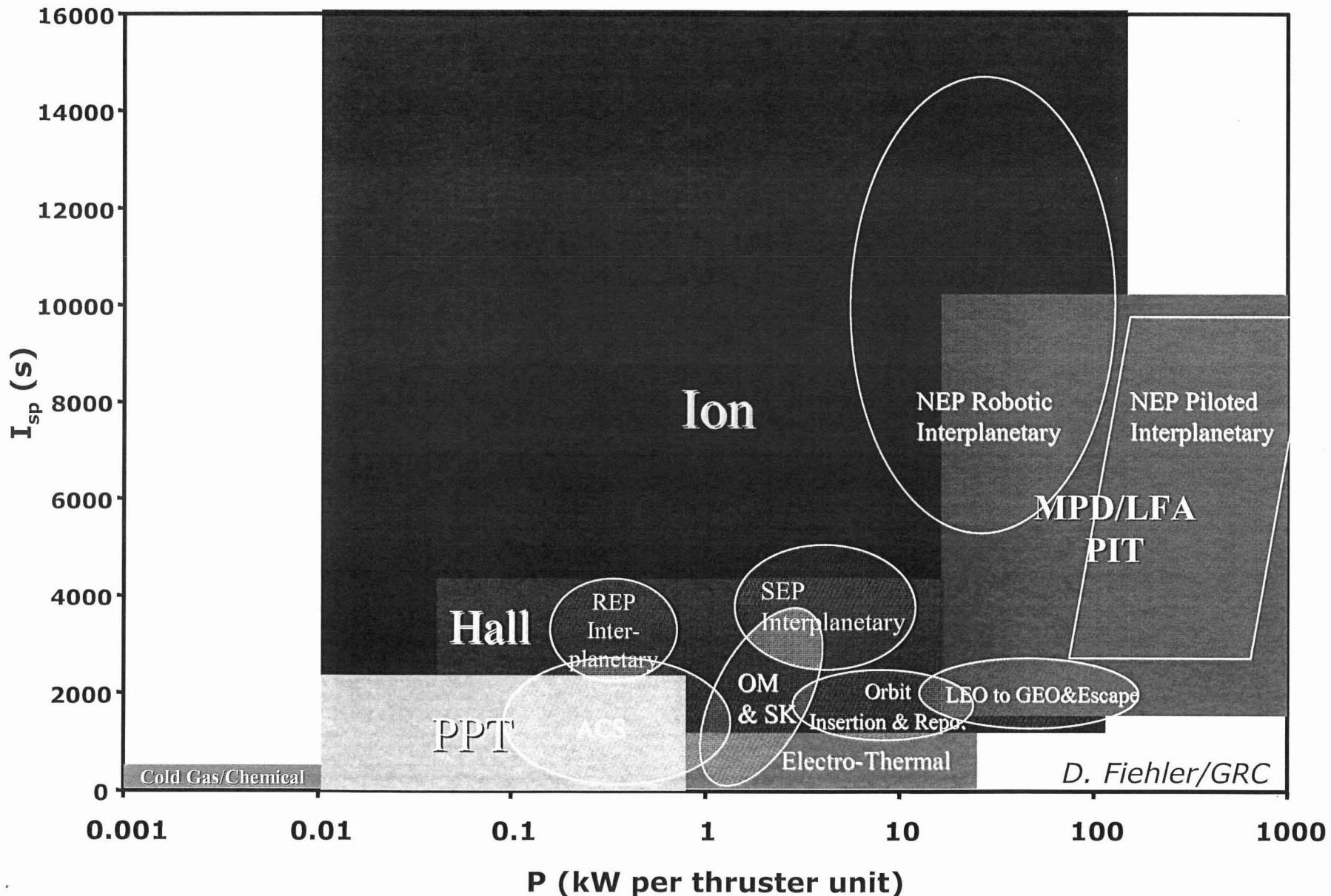
**Pulsed Plasma** thrusters use a pulsed, repetitive current to ablate solid propellant, induce magnetic field ( $J \times B$ )



**Magnetoplasmadynamic** thrusters use a high power, steady-state current to ionize gas propellant, induce magnetic field ( $J \times B$ )



# Performance Regimes





# In-Space Propulsion Technology Program Solar Electric Propulsion Task Areas

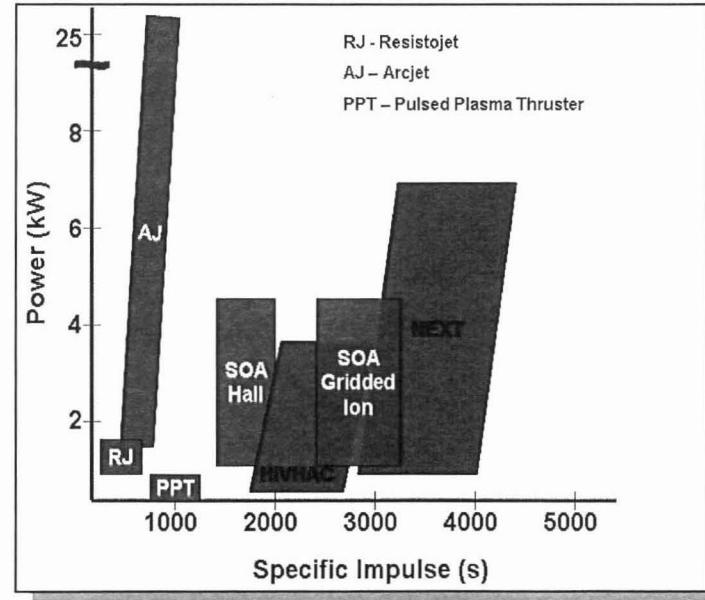


## Primary SEP Tasks

- NEXT: NASA's Evolutionary Xenon Thruster
- HiVHAC: High Voltage Hall Accelerator
- Standardize thruster power and propellant flow systems to reduce costs

## Objectives

- Expand the mission envelope of ion and hall thrusters
  - Extend thruster lifetime
  - Extend power range
  - Increase specific impulse
  - Expand SEP system capability to enhance or enable robotic earth and space science missions

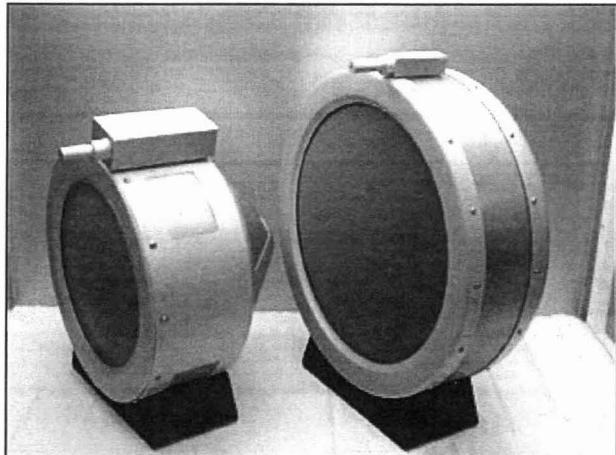


J. Dankanich/MSFC



## NASA's Evolutionary Xenon Thruster (NEXT)

- NSTAR 30-cm thruster flew on successful NASA Deep Space 1 mission, will be used on DAWN asteroid rendezvous mission (launch FY07)
- NEXT 40-cm thruster will expand SOA ion thruster capabilities to benefit Discovery/New Frontiers and other NASA science missions
  - Reduces number of thrusters required for demanding SMD science missions, reduces total system mass, improves thruster service life



Thruster Attribute	NSTAR <sup>1</sup>	NEXT
Max. Input Power, kW	2.3	Up to 7
Throttle Range	4:1	Up to 10:1
Max. Specific Impulse, s	3,170	4,190
Efficiency @ Full Power	62%	71%
Propellant Throughput, kg	235	>300 (design)
Specific Mass, kg/kW	3.6	~2.5

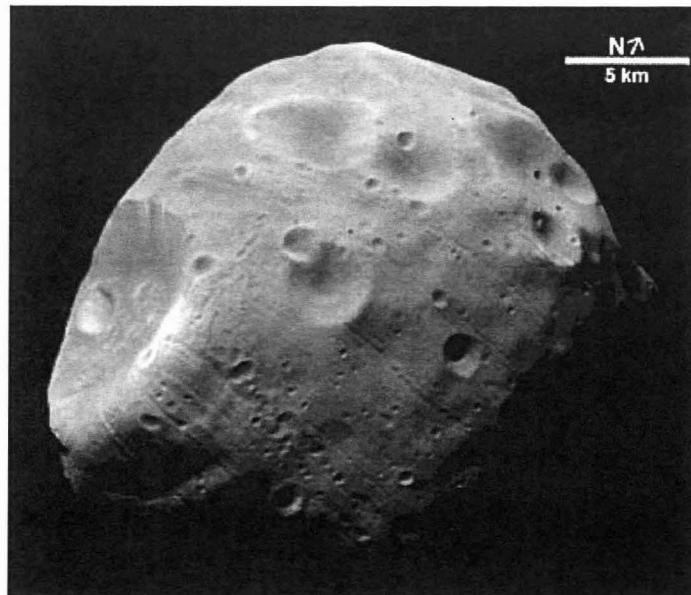
<sup>1</sup>NASA Solar Electric Propulsion Technology Application Readiness



## Mission Applications

Configuration	Typical Mission	System Input Power Range	Thrust Range	Total Component Mass (excl. DCIUs)
1+1	Discovery	0.6 - 7.2 kW	25 - 236 mN	115 kg
2+1	Discovery, New Frontiers	0.6 - 14.4 kW	25 - 472 mN	172 kg
3+1	Flagship	0.6 - 21.6 kW	25 - 708 mN	229 kg

## Discovery Mission Example: Sample Return from Deimos<sup>1</sup>



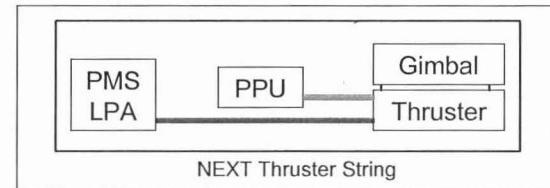
- NEXT SEP system
  - 1 operating thruster +1 spare
- Solar array power (1AU, BOL): 10-kW
- Launch Vehicle: Delta II-2925H
- Stay time: 90 days
- Total roundtrip transfer time: 2.91 years
- EP ΔV: 10.04 km/s
- Mass breakdown:
  - Launch mass: 1,065 kg ( $C_3 = 13.9 \text{ km}^2/\text{s}^2$ )
  - Xenon propellant mass: 230 kg
  - Final mass: 835 kg

<sup>1</sup>D. Oh and K. Witzberger, 2005



## Project Background

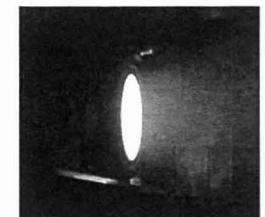
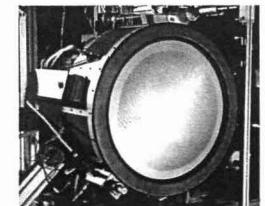
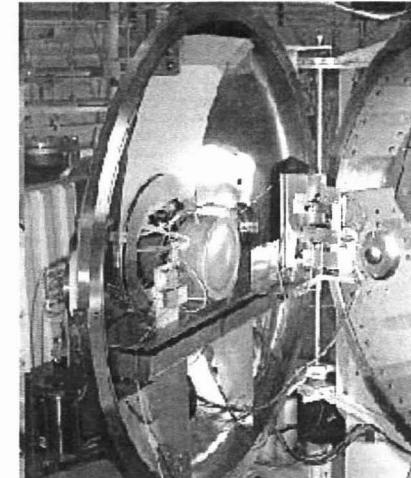
- Two-phase project to develop NEXT to TRL-5/-6
  - Sponsored by NASA Science Mission Directorate, conducted under MSFC In-Space Propulsion Technology Program
  - Implemented through competitive NRA
    - Phase 1: one-year base period, completed August 2003
    - Phase 2: multi-year (3+) option period, initiated October 2003
  - Addresses the entire ion propulsion system:
    - Thruster
    - Power processing unit (PPU)
    - Propellant management system (PMS)
    - System integration (including gimbal and control functions)
- NEXT Project Team:
  - NASA Glenn Research Center: Technology Project Lead
  - NASA Jet Propulsion Laboratory: System Integration Lead
  - Aerojet Corp: Thruster, PMS, DCIU simulators
  - L3 Comm ETI: Power processing unit
  - Participation by Applied Physics Lab, U. Michigan, Colorado State U.





## Primary Hardware

- Five NEXT engineering model thrusters built
  - Four EM thrusters used in multi thruster array test
  - EM-3 undergoing long duration performance test (initiated 6/5/05)
    - Over 5500 hours of operation and 110-kg xenon propellant throughput; exceeds NSTAR Deep Space 1 flight experience
- One prototype (flight-like) model thruster built (PM-1)
  - Delivered by Aerojet to GRC in January 2006
  - Performance acceptance testing completed at GRC
  - Thruster shipped to JPL June 2006 for comprehensive testing
    - gimbal integration, random vibration, thermal vacuum tests
- Second prototype model thruster to be built in FY07 (PM-2)
  - PM-2 thruster life test planned at GRC in FY07
  - PM-1 remains available for operational testing

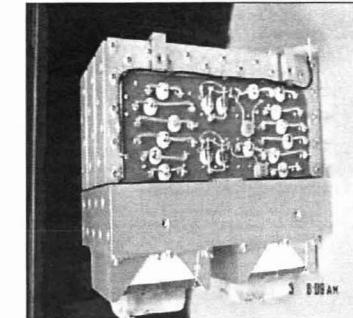




## Primary Hardware, continued

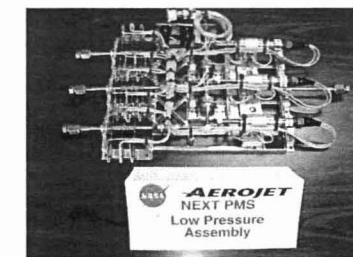
- Power Processing Unit

- Engineering model PPU in fabrication at L3 Comm ETI
- Functional testing and delivery to GRC in August 2006
- Operating characteristics:
  - Input power 0.62-kWe to 7.2-kWe
  - Main input power voltage 80-V to 160-V
  - Efficiency > 94% at peak power
  - Specific power > 0.2-kWe/kg



- Propellant Management System

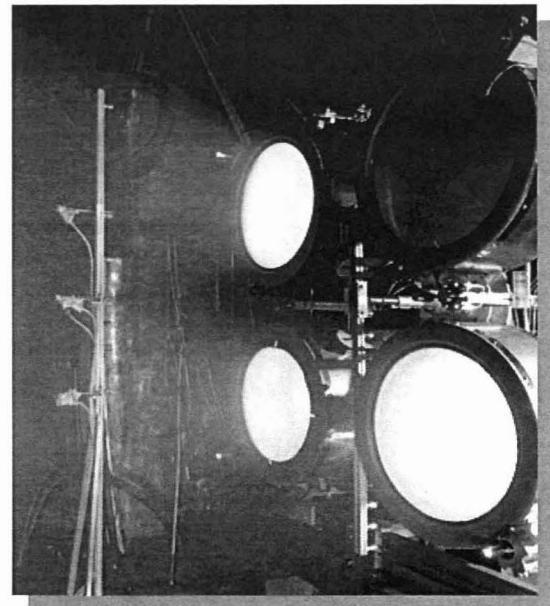
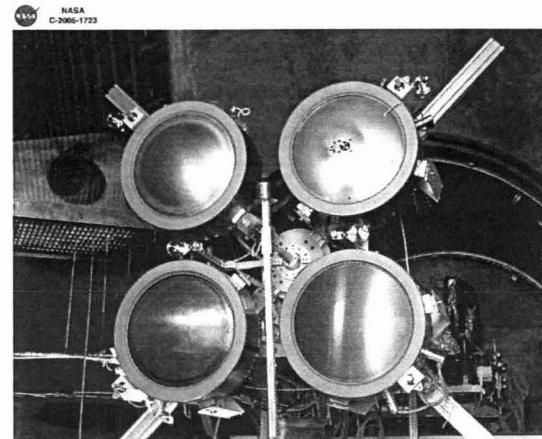
- All PMS assemblies complete
  - Two high pressure assemblies (one flight-like)
  - Three low pressure assemblies (one flight-like)
- All assemblies have completed functional tests
- Flight-like HPA and LPA have completed vibe tests, post-vibe functional tests





## System Status

- Multi-Thruster Array Test (FY06)
  - Assess thruster and plasma interactions (effect of thruster spacing, gimbaled thrusters, neutralizer operating modes)
  - Four GRC EM thrusters (three operating, one instrumented non-operating)
  - Completed December 2005 at GRC
  - Expected performance achieved; well understood operations, no significant sensitivity to system configuration
- System Integration Test (FY07)
  - PM thruster, EM PPU, flight-like HPA and LPA, gimbal and DCIU simulator
- System Service Life Analysis (On-going)
  - Thruster life modeling and analysis





## High Voltage Hall Accelerator (HiVHAC)

- Optimize Hall thrusters for NASA SMD missions
  - Operate at high voltage (~ 1000-V) to increase specific impulse
  - Operate at higher power density to increase thruster efficiency
  - Mitigate channel erosion to increase throughput and total impulse
- Primary HiVHAC Products:
  - SOA Design: NASA-94-M thruster with discharge channel walls thick enough to enable 150 kg of propellant throughput (GRC/Aerojet led design)
  - Advanced SOA Design: NASA-103M thruster with in-situ replacement of eroded channel walls to enable 300 kg of propellant throughput (GRC led design)
  - Numerical simulations of discharge channel erosion, validated with detailed experimental diagnostics using NASA-77M thruster (GRC, U. Michigan)





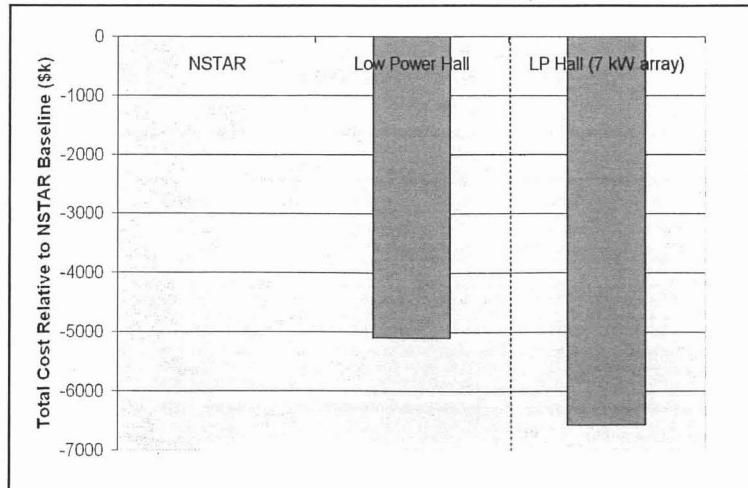
## High Voltage Hall Accelerator (HiVHAC)

- Design Objectives:

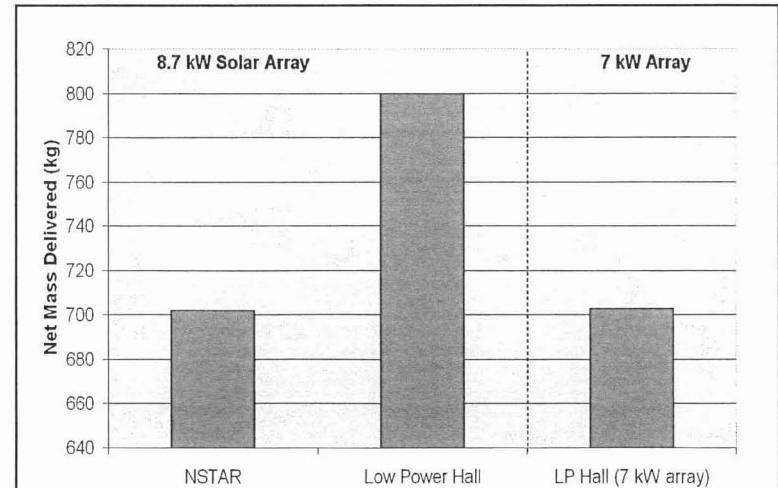
Input Power	0.3 – 3.6 kW
Specific Impulse	1600 – 2700 s
Efficiency	> 60%
Thrust	20 – 150 mN
Propellant Throughput	>150 kg (SOA) >300 kg (ASOA)
Specific Mass	1.3 kg / kW
Operational Life	> 10,000 hrs

*Combined with lower system complexity, low power HiVHAC thrusters offer significant benefits for NASA Discovery missions*

- Mission Example: DAWN cost and performance comparison



Reduced cost relative to NSTAR baseline

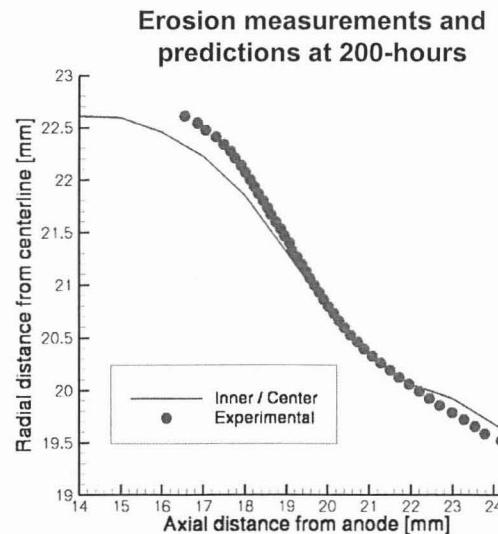
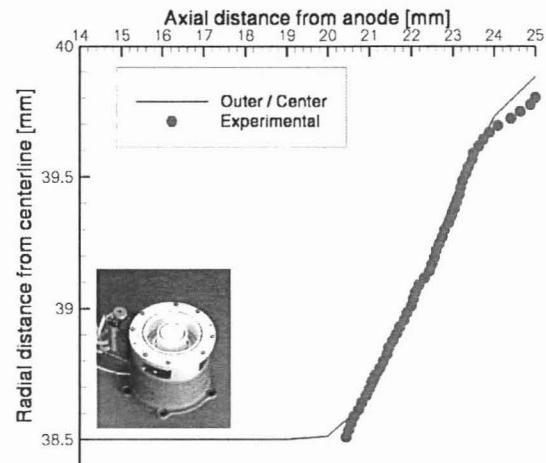


Increased payload relative to NSTAR baseline



## Erosion Simulations and Model Validation

- ◆ Provide erosion data to validate hall thruster channel erosion models
- ◆ Erosion measured during wear test of NASA-77M thruster:
  - 1.75-kWe (500 V, 3.5 A,  $118 \text{ mA/cm}^2$ )
  - Operated at lower power density to increase total operating time (limited by thruster wall thickness)
  - Wear profiles of inner and outer channel walls measured every 100 hours
  - Thruster performance measured continuously
- ◆ Channel walls were significantly eroded after 300-hours of operation
  - channel replaced and wear test continuing in order to gather additional erosion data





## Additional Wear Testing with Aerojet BPT-4000 Thruster

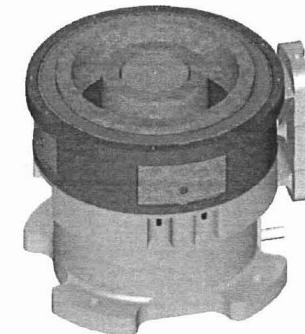
- BPT-4000 previously qualified by Aerojet with a 5600 hour life test
  - Lockheed-Martin/USAF customer
- NASA sponsored a 1000-hour life test extension (through June 2006)
- Additional wear data to improve fidelity of Hall thruster erosion models
- Depending on funding, Aerojet can extend life test to longer duration
  - Opportunity to evaluate use of commercial thrusters for NASA missions

BPT-4000	Thrust (mN)		Specific Impulse (sec)	
	End of Life Test	Start of Life Test Extension	End of Life Test	Start of Life Test Extension
3.0 kW–300 V	190	191	1839	1842
3.0 kW–400 V	171	172	2012	2008
4.5 kW–300 V	278	278	1963	1976
4.5 kW–400 V	254	256	2151	2162

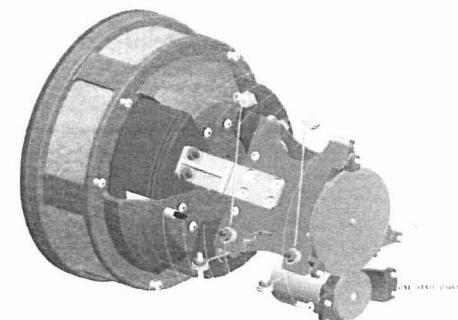


## **SOA and ASOA Thruster Status**

- NASA-94M (SOA)
  - Aerojet fabrication of the State-of-Art (SOA) laboratory model thruster NASA-94M expected to be complete in late June 2006, followed by acceptance testing at GRC
- NASA-103M (ASOA)
  - Vendor fabrication of the Advanced State-of-Art (ASOA) laboratory model thruster NASA-103M expected to be complete by late July 2006, followed by acceptance testing at GRC
- Extended duration tests of SOA and ASOA thrusters planned for FY07



SOA

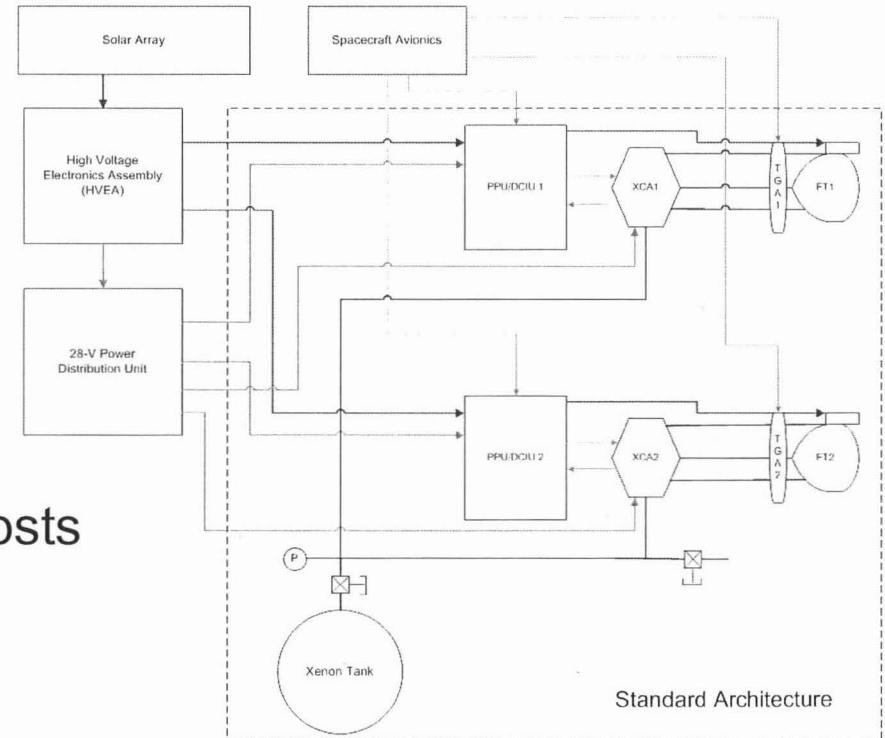


ASOA



**Objective:** reduce electric propulsion system non-recurring engineering costs by standardizing components and increasing manufacturability of sub-systems

- Single-string architecture to reduce system costs
- Operate various thrusters to match mission needs
  - NEXT, NSTAR, possibly commercial thrusters (XIPS)
- Standardize power supply topologies
- Embed DCIU to reduce production costs
- Standardize propellant management systems (LPA, HPA, VACCO, etc)



## **Status:**

- PPU/DCIU design selection in FY06, initiate procurement in FY07



## **Objective:** improve method for thruster life qualification

- Thruster life qualification for SMD missions currently require several thousand to tens of thousands of hours of vacuum ground tests
  - Expensive and time consuming; roadblock to user acceptance
- Ongoing activities at NASA centers, industry, and universities to model ion and hall thruster erosion characteristics, predict thruster lifetimes
  - Ion grid erosion
  - Discharge cathode erosion
  - Hall thruster chamber erosion
- Need to establish a set of standards for electric propulsion thruster life qualification using combination of numerical models and limited ground test validation
  - Establish expert working group to develop standards, with SMD and TMCO participation (represent user community)
  - Identify, develop and validate remaining ion and hall thruster life models
  - Publish standards documents for community acceptance and use

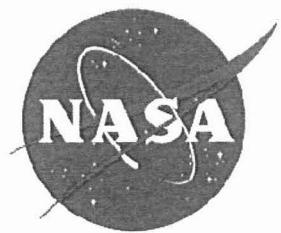


For additional information on Solar Electric Propulsion within the In-Space Propulsion Technology Program, please contact:

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